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The researchers developed code for integrating envelope equations derived from scalar Maxwell's equations for a scalar field coupled to the SCB equations. This code can handle plane wave (one dimensional) and a single transverse dimension (two dimensional). At this time, the codes are being used to study the behavior of ultrashort pulses propagating in the nonlinear medium. The case of a simiconductor amplifier has been the focus. They have been able to integrate the plane wave equations for considerably longer propagation distances than had been possible previously due to the efficiency of the algorithm. In so doing, they have predicted novel effects such as pulse compression, the appearance of an adiabatic following behavior, and spontaneous pulse breakup for very high gain amplifiers. In addition they have made a study of the interactions in such an amplifier of simultaneous ultrashort strong pulses at different frequencies. This is relevant to the ability of such a device to be used with frequency multiplexing.

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Ultrashort Pulse Effects in Semiconductor Amplifiers and in Dispersive Media

April 1994

Arizona Center for Mathematical Sciences
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The Arizona center for Mathematical Sciences is currently involved in two investigations that are funded by AFOSR. One of these has been underway since November 1993 and involves the study of ultrashort laser pulse effects in the eye. The other started this February, and involves study of dynamics in semiconductor amplifiers and lasers. Both of these projects involve large scale computation, and code development for a massively parallel platform.

Semiconductor amplifiers and lasers

Our goal is to use models for the optical behavior of semiconductors based on an understanding of the underlying physics to develop and test a heirarchy of equations and numerical codes for modeling semiconductor behavior. The goal is reasonable because the basic physics describing the optical properties of semiconductors is well developed. It is challenging because that physics happens over an extreme range of time scales, from carrier-carrier collision effects at a femtosecond scale to heat diffusion on a millisecond scale. To predict the behavior of a device we would like to have model equations, derived from the underlying physics, which do not require that the full range of time scales be resolved. Different applications or questions will require the use of different model equations, but all must be mutually consistent.

Our starting point in this study has been Maxwell's equations coupled to the semiconductor Bloch equations (SCB). The SCB equations describe the many body interactions among the electrons and holes in the semiconductor due to Coulumb effects and optical interactions. We are developing and testing a Maxwell solver to integrate full vector Maxwell in one two or three dimensions. At this time that equation is being integrated coupled to a simple two oscillator material equation. Our next step with this code is to couple the SCB equations into the code.

We have also developed code for integrating envelope equations derived from scalar Maxwell's equations for a scalar field coupled to the SCB equations. This code can handle plane wave (one dimensional) and a single transverse dimension (two dimensional). At this time, the codes are being used to study the behavior of ultrashort pulses propagating in the nonlinear medium. The case of a semiconductor amplifier has been our focus. We have been able to integrate the plane wave equations for considerably longer propagation distances than had been possible previously due to the efficiency of our algorithm. In so doing, we have predicted novel effects such as pulse compression, the appearance of an adiabatic following behavior, and spontaneous pulse breakup for very high gain amplifiers [?]. In addition we

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have made a study of the interactions in such an amplifier of simultaneous ultrashort strong pulses at different frequencies [?]. This is relevant to the ability of such a device to be used with frequency multiplexing.

We have also completed preliminary studies of the behavior of beams with transverse structure in such amplifiers. At this time we are focusing our efforts on improving the implementation of this code on the CM5 at AHPCRC at Minnesota Supercomputing Center. This has proved a challenging task. The nature of the problem is well adapted to a massively parallel distributed memory model, since a domain decomposition distributing calculations to processors depending on the value of the transverse spatial variable leads to calculations being performed almost entirely in local memory, with extremely little cross processor communication required. (Only the diffractive term in the field equation couples different transverse spatial locations — the field represents less than 1% of the data in memory, and its propagation requires less than 0.01% of the CPU demand of the program.) However, our initial efforts to implement this approach have taught us that the programming model provided by CM FORTRAN leads to a great deal of cross processor communication that is extremely difficult to control[1]. We have had some success in improving the parallelization of the code, and have realized speedups using 32 processors (128 vector units) of a factor of 25 over single processor code, but the size of our problem is such, that we feel it is worthwhile to achieve maximum parallelization, which should be very close to a factor of 120. This is particularly important since we plan to study the behavior of these equations when a cavity is added, so that the system lases. This will require much longer calculations than those currently being made.

Ultrashort pulse propagation in the eye

Researchers at the Armstrong Laboratory, Brooks AFB are involved in setting safety standards for ultrashort laser pulses. No reliable standard currently exists for picosecond and sub-picosecond pulses. For femtosecond pulses it appears that the very high powers contained in low energy pulses can induce a nonlinear self-focusing of the pulse leading to plasma generation [?]. We are involved in modeling the propagation of ultrashort pulses in dispersive media, such as the fluid in the eye. These equations are nonlinear, and in one approximation, they lead to the two dimensional nonlinear Schrödinger equation with a focusing nonlinearity. This equation has singularities, corresponding to a collapse of the optical beam, after a finite propagation distance. In fact, estimates of the values of the various parameters in this simple model and the powers used in the laboratory lead to a distance to collapse somewhat smaller than the length of the eye. Thus one possible mechanism for the observed threshold is beam collapse. As useful as those simple models are in getting a feel for the behavior of the system, there are very important effects that are omitted. We are now investigating the behavior of the system when some of those effects are included. In particular, the medium

[1]Our experience with the CM5 is based on a beta release of the software, and may not reflect the behavior of later releases

through which the pulse is propagating has dispersion. This dispersion could arrest the collapse, since it tends to spread the energy out along the direction of propagation at the same time as the collapse is concentrating it radially. Whether the collapse is arrested or not, it is useful to be able to say what the intensities will be within the eye. We have derived simplified equations estimating these effects, and compared them to direct numerical simulations of model equations including dispersion, diffraction and self phase modulation [?, ?, ?]. If the collapse proceeds sufficiently far, nonparaxial effects may become important. The Maxwell equation solver mentioned in the previous section will be used to study such effects. This is numerically quite challenging, since the Maxwell solver must resolve the optical wavelength. The three dimensional vector Maxwell code requires a great deal of memory as well as very significant amounts of CPU. This code has been implemented in FORTRAN 90 on both the Cray C90 at WES and the CM5 at AHPCRC. It parallelizes quite well, though as in the case of the semiconductor propagation code, it is not a simple as one would hope to achieve the amount of parallelization potentially present in the algorithm while working with CM FORTRAN. Another potentially important effect that we are modeling is the formation of a plasma. The form of the nonlinearity in a plasma is defocusing, so if a plasma forms (due to the high intensities of the self focusing beam), it may arrest that collapse.

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